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# QFT nonlinearities in vacuum and plasmas.

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# QFT nonlinearities in vacuum and plasmas

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# Collaborators

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- J. T. Mendonça (IST)

# Overview

- Why are we interested in the low energy quantum vacuum and high field physics?
- Plasmas and the quantum vacuum topically connected.
- How can we probe the vacuum?
- Quantum effects in plasmas.
- Examples.
- What might the future bring?

# Developments

- New developments in extreme plasma systems and lasers. (Dunne, Nature Phys., 2006); Buchanan, Nature Phys., 2006)
- Current divide: relativistic optics & nonlinear QED. (Mourou et al., RMP, 2006; Marklund & Shukla, RMP, 2006; Salamin et al.Phys. Rep., 2006)
- New developments in numerical and experimental tools. (e.g. Fonseca, Proc. HPCPAST 2002; Trines et al., PRL, 2005)
- Near future importance: laboratory astrophysics, e.g. hydro, nuclear astro. (Remington et el., RMP, 2006))

- Questions in fundamental physics:
  - Photon-photon scattering. (Schwinger, PR, 1951; Bernard et al., Eur. Phys. J. D, 2000; Lundström et al., PRL, 2006)
  - Hawking-Unruh effect. (Hawking, Nature, 1974; Unruh, PRD, 1976; Chen & Tajima, PRL, 1999; Schützhold et al., PRL, 2006, 2008)
  - Axion-like particle searches. (Wilczek, PRL, 1978; Gies, J. Phys. A, 2008)
  - ... etc.

# Soluble models

Exact solutions:

> *In eighteen-century Newtonian mechanics, the three-body problem was insoluble. With the birth of general relativity around 1910 and quantum electrodynamics in 1930, the two- and one-body problems became insoluble. And within modern quantum field theory, the problem of zero bodies (vacuum) is insoluble.*
>
> R.D. Mattuck
>
> *A Guide to Feynman Diagrams in the Many-Body Problem* (1976)

➡ We need methods, experimental and theoretical, to deal with such issues.

# The quantum vacuum

- Quantum electrodynamics: fundamental theory of photon-matter interactions.
- 1930's: Weisskopf, Heisenberg, Euler etc. + Dirac discovers nonlinear quantum vacuum.
- 1950's: Schwinger shows vacuum polarization from QED.
- Special relativity + Heisenberg's uncertainty principle → vacuum acts as virtual pair plasma [e.g. RMP, 2006].
- Quantum vacuum: from NEMS to QG.

# Signs of QFT vacuum on photons

a) Nonlinear electrodynamics.
- QED vacuum polarization (Schwinger field).
- String theory Born–Infeld electrodynamics (string tension) (Tsetylin, hep-th/9908105).
- Minicharge particles?

b) Phase- and polarization effects.
- Axion-like particles.
- Vacuum birefringence (QED, LQG, ST foam).

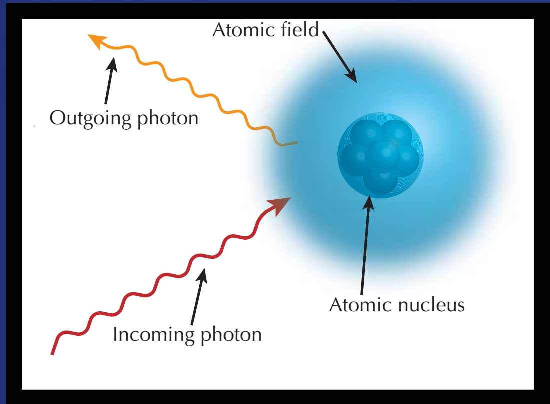
c) Vacuum dispersion
- Derivative QED corrections.
- Spacetime coarsening:
  - Loop QG.
  - Non-commutative ST.
  - Double special relativity.

Nonlinearities + dispersion?

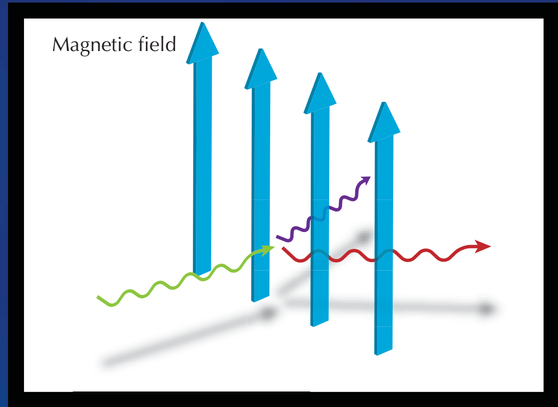
Hawking effect, BH entropy.

# Nonlinear vacuum effects

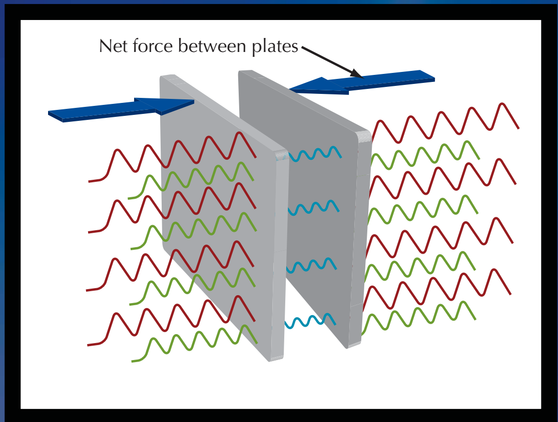
## Delbrück scattering



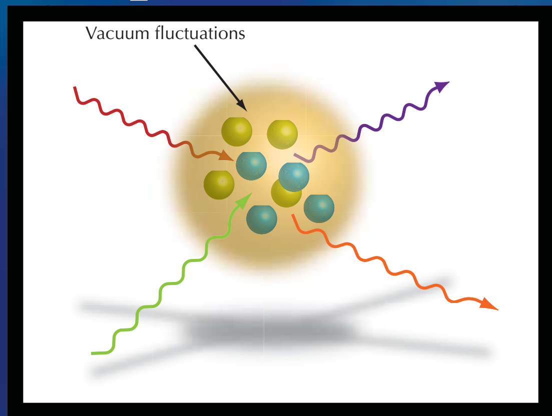

## Photon splitting




## Casimir effect



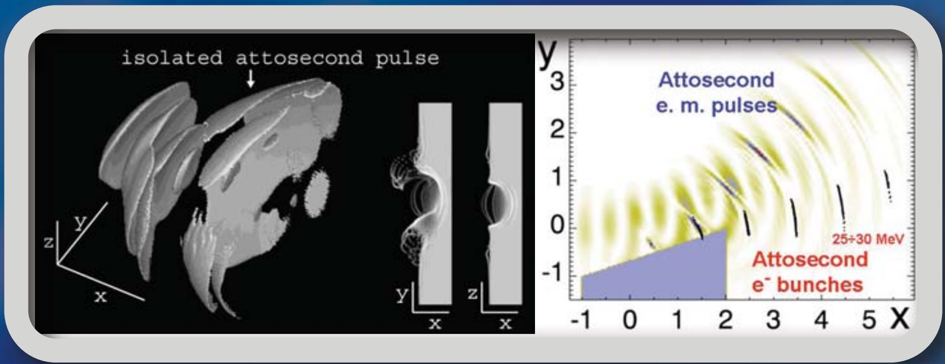

## Elastic photon scattering



# High field generation

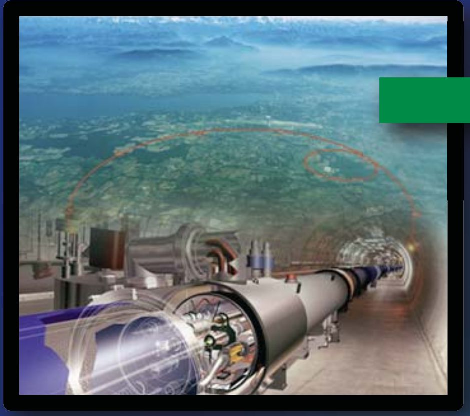
- Many high phenomena directly tractable with next generation laser systems.
- Some phenomena require intensities above current experimental limits.
- Attosecond electron bunches creates mirror (Naumova et al., PRL, 2004; Nees et al., J. Mod. Opt., 2005; Thaury et al., Nature Phys., 2007).

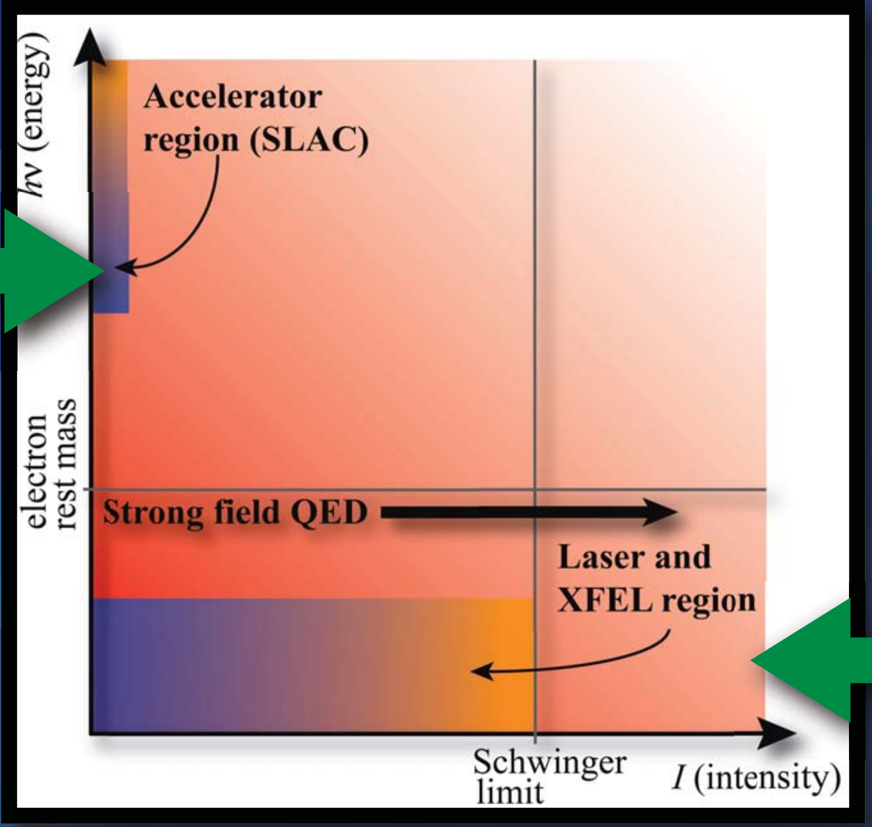
Opportunity to reach the Schwinger field $\sim 10^{29}$ W/cm$^2$

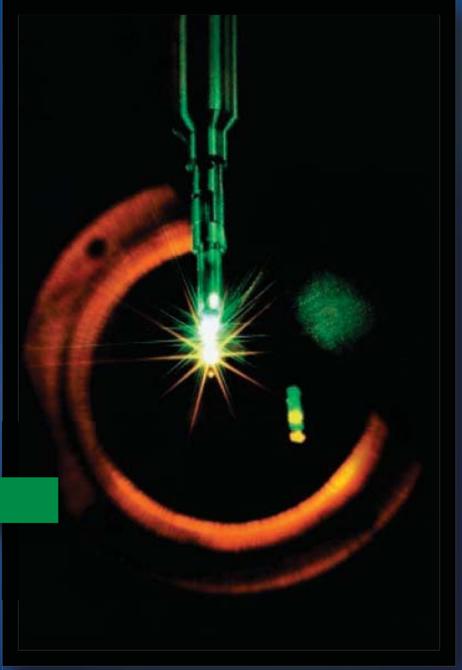


# Probing new regimes

> Accelerators vs. laser systems:





# Probing new regimes

- New possibilities to probe low-energy domains.
- In particular, light pseudo-scalar particles (e.g. PVLAS, Fermi Lab, DESY...).
- Necessary (?) modifications to the Standard Model (Gies, J. Phys. A, 2008).
- Is it possible to probe Lorentz invariance properties (dispersion)?
- Parametrized  theory to restrain models.

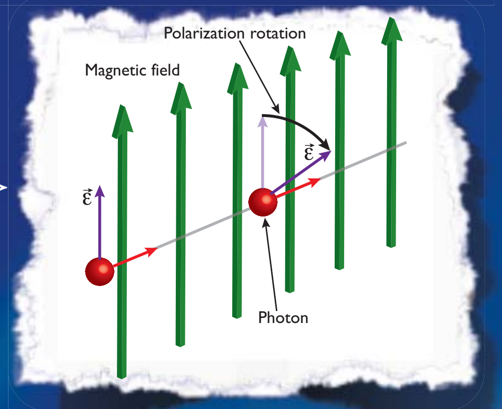
# Why?

## Astrophysics

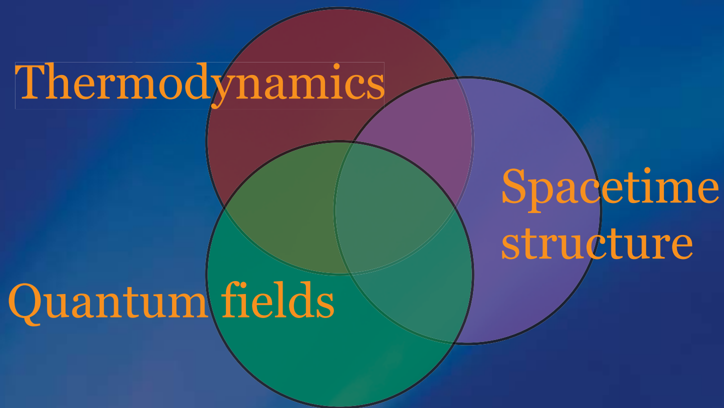
Giga-gauss field in laser-plasmas.

## Modify the Standard Model?

$g\phi\,\boldsymbol{E}\cdot\boldsymbol{B} \Rightarrow$




## A touch of gravity




## New physics

High precision intense optical experiments → ?

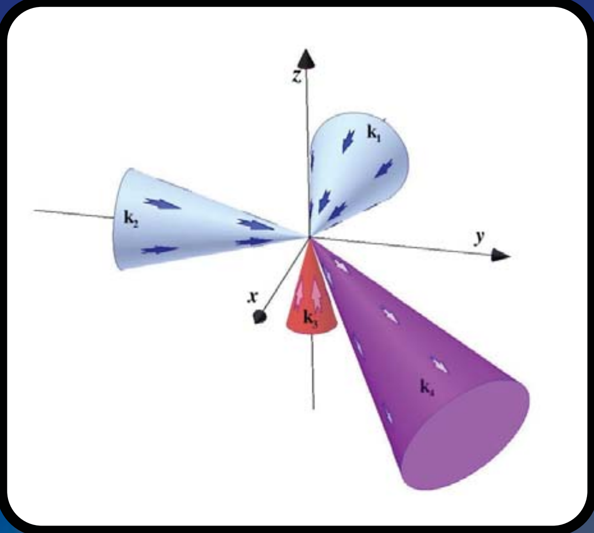
Gies, J. Phys. A **41**, 164039 (2008)

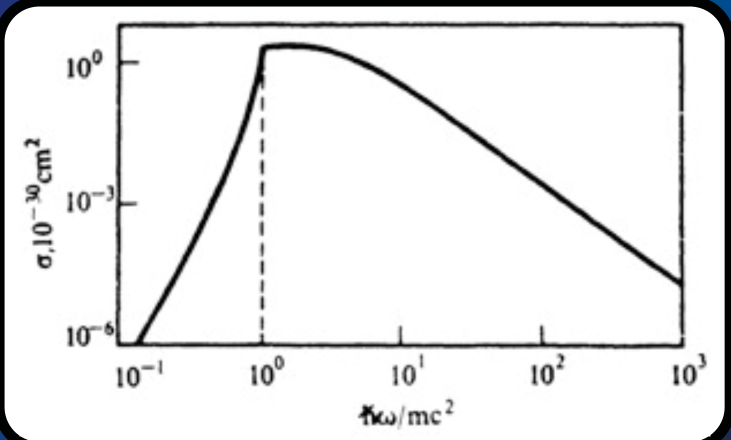
# Example: photon–photon scattering

$$\sigma_{\gamma\gamma} \approx 0.7 \times 10^{-29} \left(\frac{\hbar\omega}{1\,\mathrm{MeV}}\right)^6 \mathrm{cm}^2$$

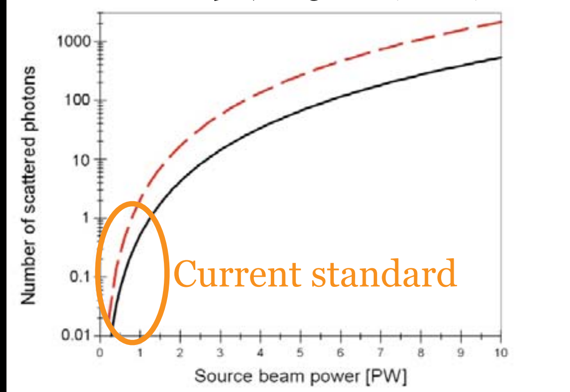
$$\mathcal{L} = \mathcal{L}_0 + \frac{\epsilon_0 \alpha}{90\pi E_{\mathrm{crit}}^2}\left[\left(E^2 - c^2B^2\right)^2 + 7c^2(\boldsymbol{E}\cdot\boldsymbol{B})^2\right]$$

$$E_{\mathrm{crit}} = m_e^2 c^3/e\hbar \sim 10^{16}\,\mathrm{V/cm}$$




PRL **96**, 083602 (2006)




Moulin & Bernard, Opt. Comm., 1999; Bernard et al., EPJD, 2000; Di Piazza et al., PRD, 2005; Lundin et al, PRA, 2006.

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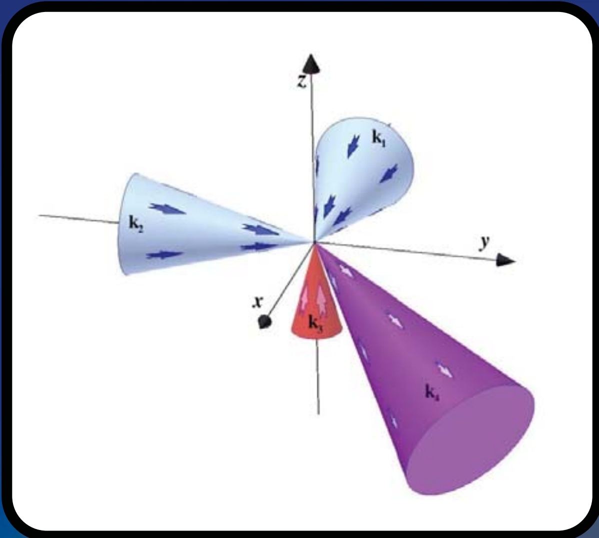


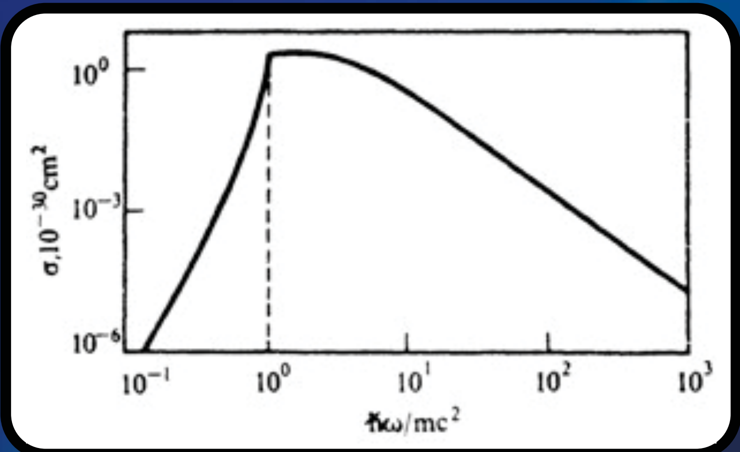


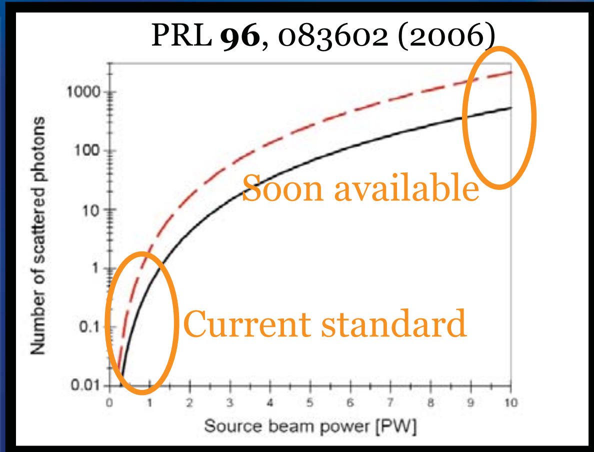


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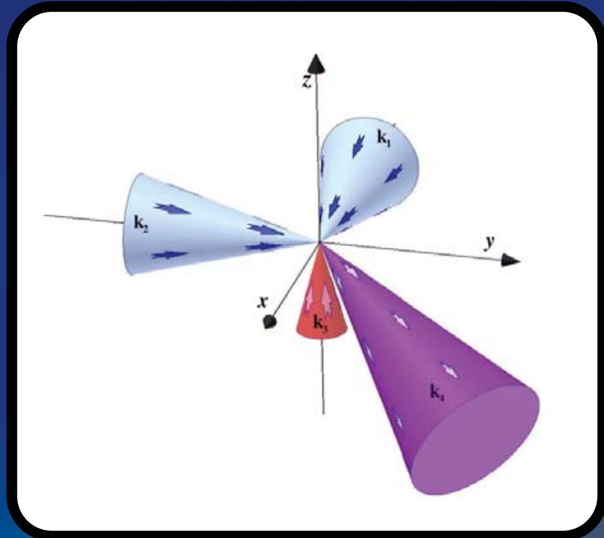
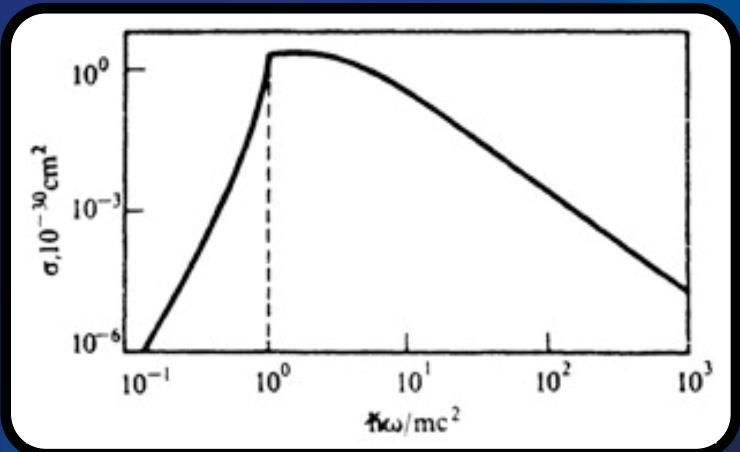
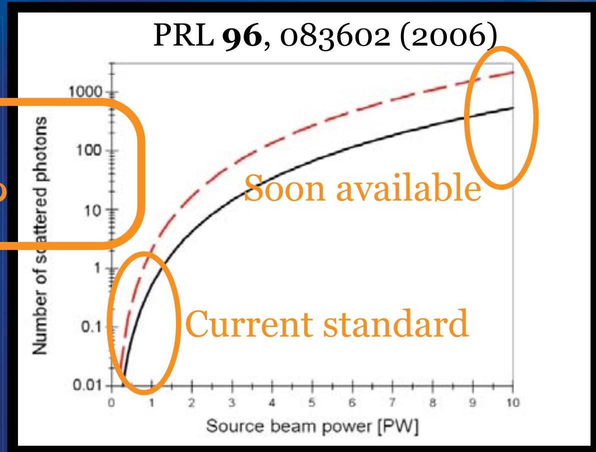



Deviations:
new physics?




Moulin & Bernard, Opt. Comm., 1999; Bernard et al., EPJD, 2000; Di Piazza et al., PRD, 2005; Lundin et al, PRA, 2006.

# Example: photon–photon scattering

- Why? (See also Tommasini's talk!)
  - "Clean" vacuum experiment.
  - Benchmark for experimental development.
  - Could new physics be probed?
  - Constraining nonlinear electrodynamics:

$$\mathcal{L}_{BI} = \kappa^2 \left[ 1 - \sqrt{1 + \frac{\kappa^{-2}}{2}(E^2 - B^2) - \frac{\kappa^{-4}}{16}(\mathbf{E}\cdot\mathbf{B})^2} \right]$$

- Derivative corrections to HE lagrangian

$$\mathcal{L}_D = \sigma\epsilon_0 \left[ (\partial_a F^{ab})(\partial^c F_{cb}) - F_{ab}\Box F^{ab} \right]$$

(Mamaev et al., Sov. J. Nucl. Phys. **33**, 569 (1981))

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Prop. to Compton wavelength^2

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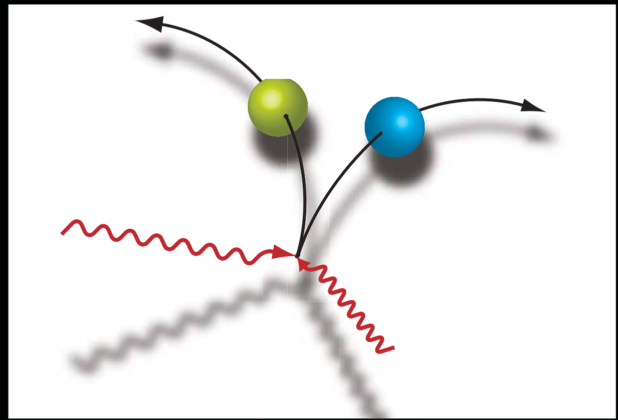
(Mamaev et al., Sov. J. Nucl. Phys. **33**, 569 (1981))

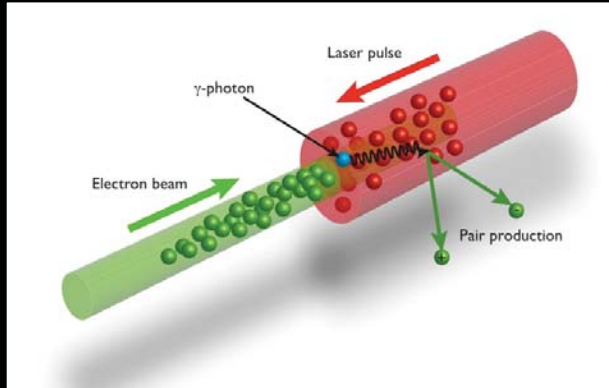
# Pair production

$\hbar\omega_\gamma \gtrsim 2m_e c^2$

$$\begin{cases} \gamma + \gamma \to e^- + e^+ \\ \gamma + B_0 \to e^- + e^+ + B_0 \end{cases}$$

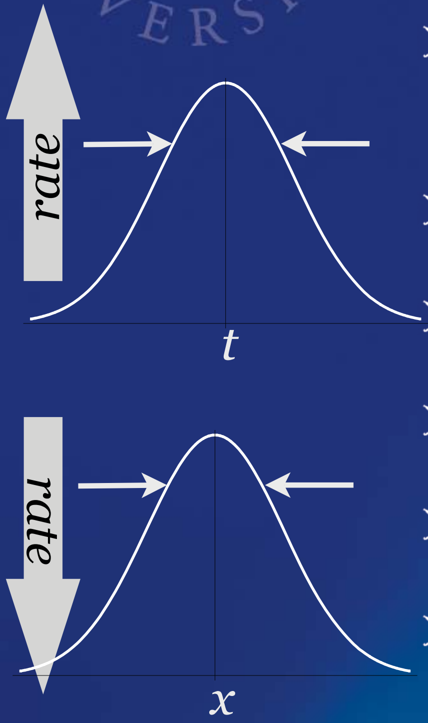


- Positronium interaction with laser: Small scale muon pair collider! (Müller et al. PRD **74**, 074017 (2006)).
- Laser-pair plasma interactions give new experimental possibilities.



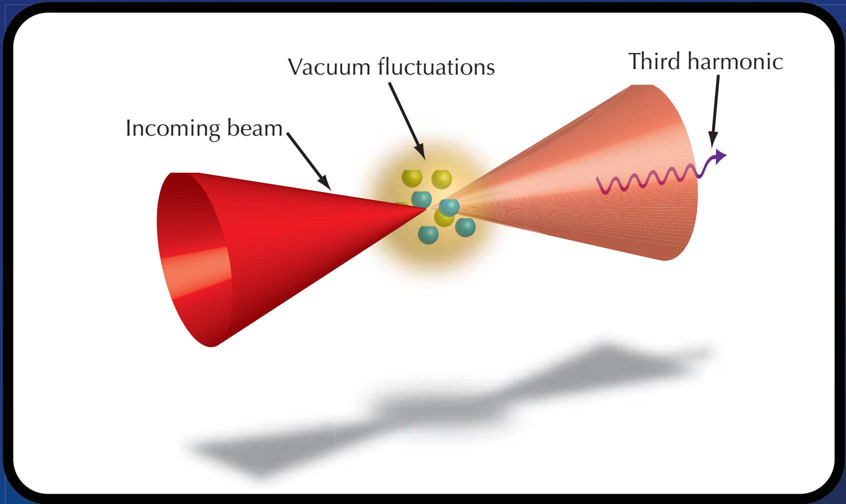

Burke et al., PRL **79**, 1626 (1997))

# Pair production




- “Schwinger mechanism” for fields with spatial *and* temporal variation.
- Temporal compression: *increased* production rate.
- Spatial compression: *lower* production rate.
- Laser fields → production rate unknown.
- Schwinger limit: more than necessary?
- Need for theory (e.g. world-line instantons, e.g. Gies, Dunne).
- Will experiment come first? Non-perturbative aspect of QED.

# Harmonic generation




- Vacuum harmonics possible in principle (Di Piazza *et al.*, PRD **72**, 085001 (2005); Fedotov & Narozhny, PLA **362**, 1 (2007)).
- Nonperturbative surprises?

# Plasmas in QED vacuum

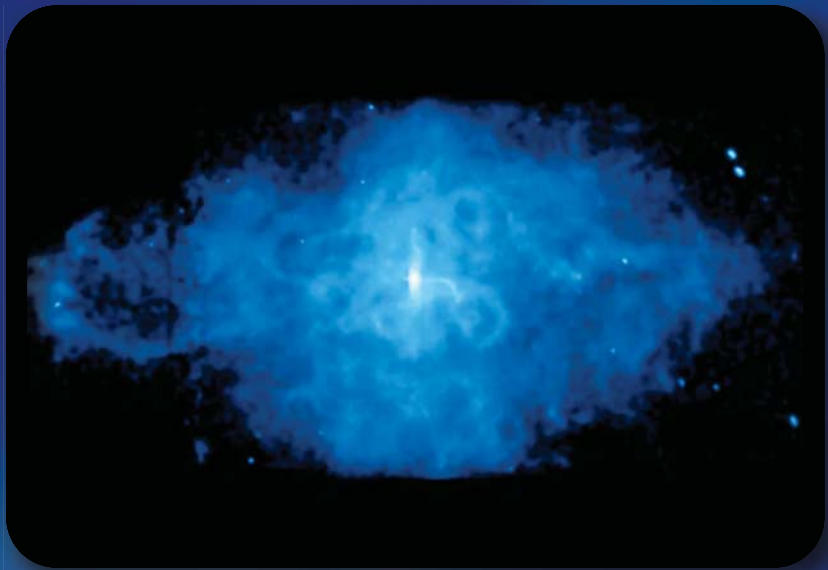
- Combined effect of ultrarelativistic magnetized plasmas and QED → new electromagnetic modes. Example:

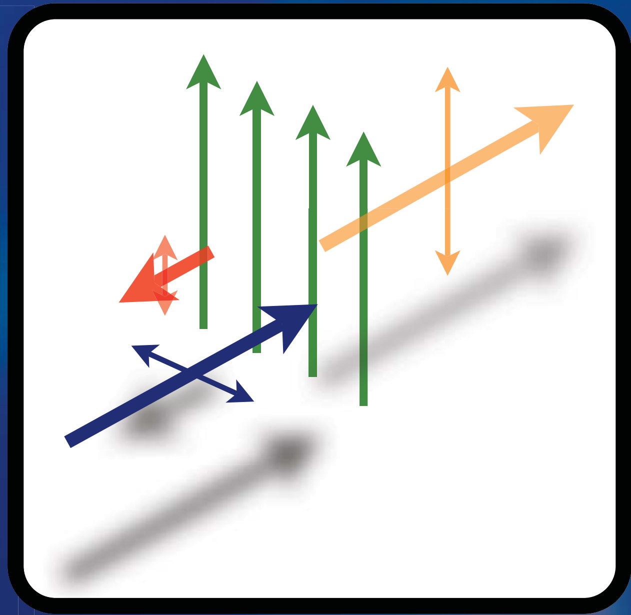
$$n^2 = \frac{4\alpha}{45\pi}\left[\left(\frac{E}{E_{\rm crit}}\right)^2 n^2 + \left(\frac{B_0}{E_{\rm crit}}\right)^2\right] n^2 \pm \frac{\hbar}{m_e}\frac{\omega_p^2}{\omega}\frac{E_{\rm crit}}{E}$$

- New dispersive properties in strong field environments, e.g. pulsar magnetospheres.
- Plasma breaks Lorentz invariance.
- Possible boost for certain plasma parameters (Di Piazza et al.)?

# Plasmas in QED vacuum

> Photons down-converted in strong vacuum magnetic field ("photon splitting") (Adler, Ann. Phys., 1971).

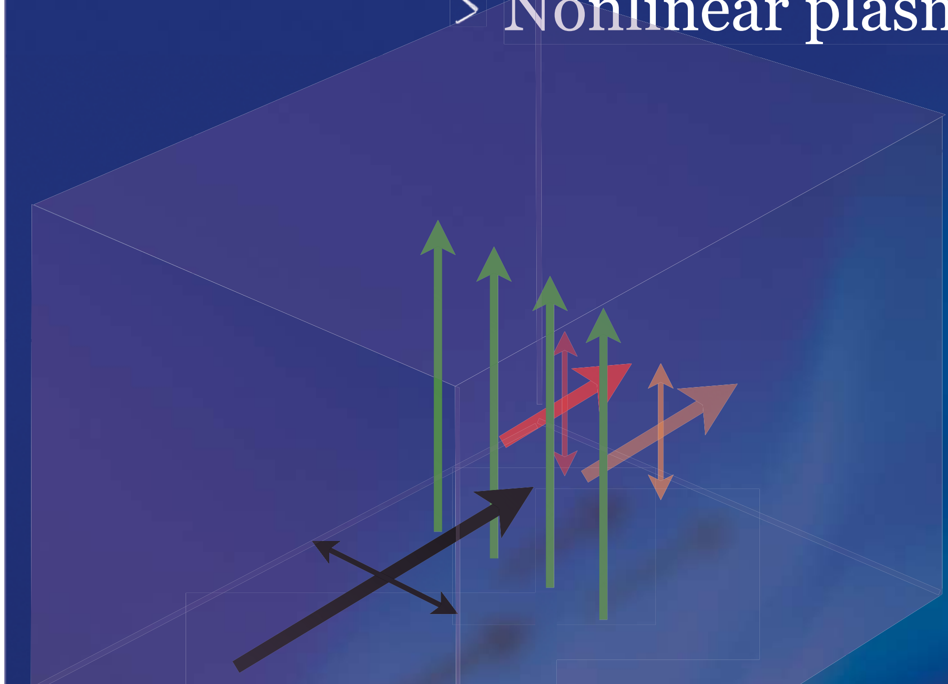




$$\gamma_{\perp} \rightarrow \gamma_{\|} + \gamma_{\|}$$

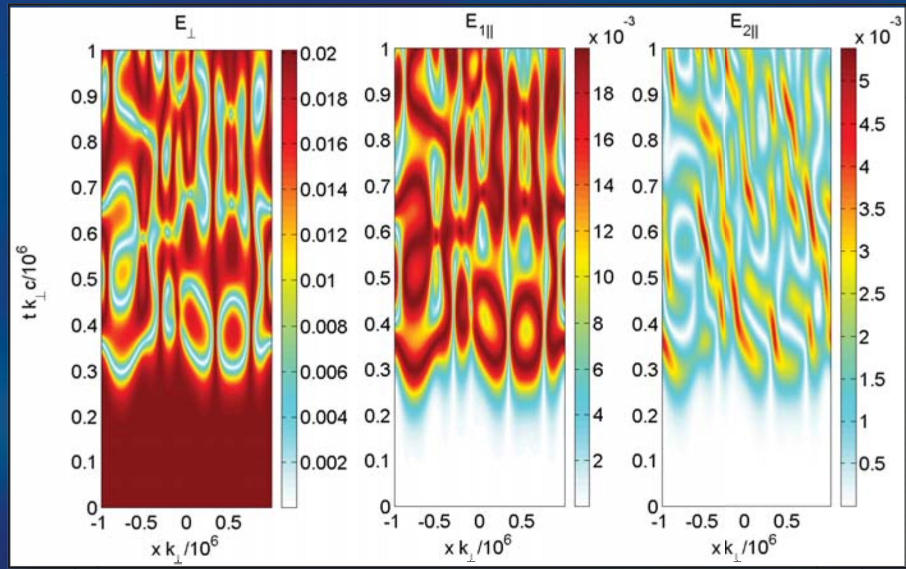
# Plasmas in QED vacuum

> Nonlinear plasma-QED photon splitting.



Linear decay channel: pair plasma suppression in pulsar magnetospheres (Shabad & Usov, Nature (1982))

Incoming wave | Decay product 1 | Decay product 2




PRL **98**, 125001 (2007)

# Colliding photons

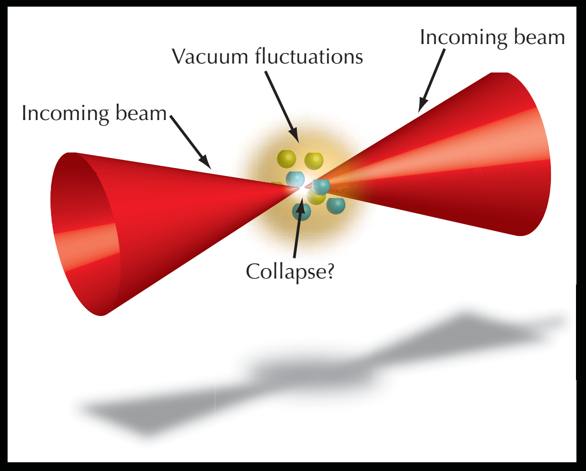
Two colliding light pulses.
Criteria for vacuum collapse:

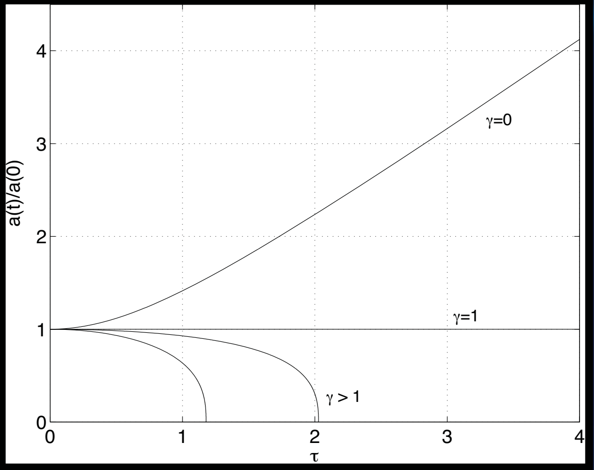
$$\left(\frac{\alpha}{90\pi}\right)^{1/2}\frac{|E|}{E_{\rm crit}} > \frac{r_p}{\lambda_p}$$

Supplemented by

$$\frac{W_p}{\lambda_p r_p^2} > \frac{90\pi}{\alpha}\epsilon_0 E_{\rm crit}^2$$

Sufficiently long pulses for collapse to occur. See also Kharzeev & Tuchin, PRA, 2007. Or pair production before Schwinger limit?



# Vacuum dynamics

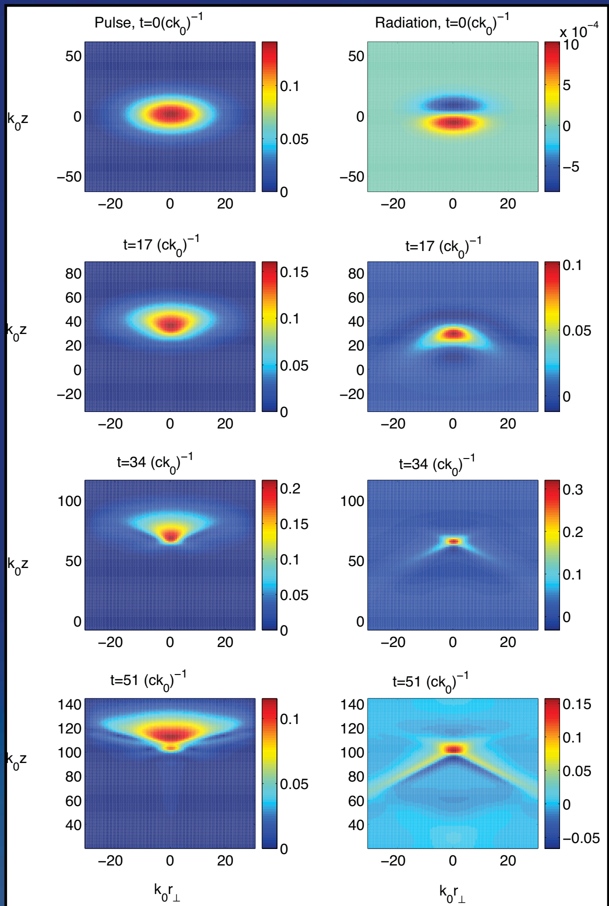
- Dynamics similar to laser-plasmas
- Catastrophic collapse governed by NLSE and acoustic wave equation
- Evolution determined by the system

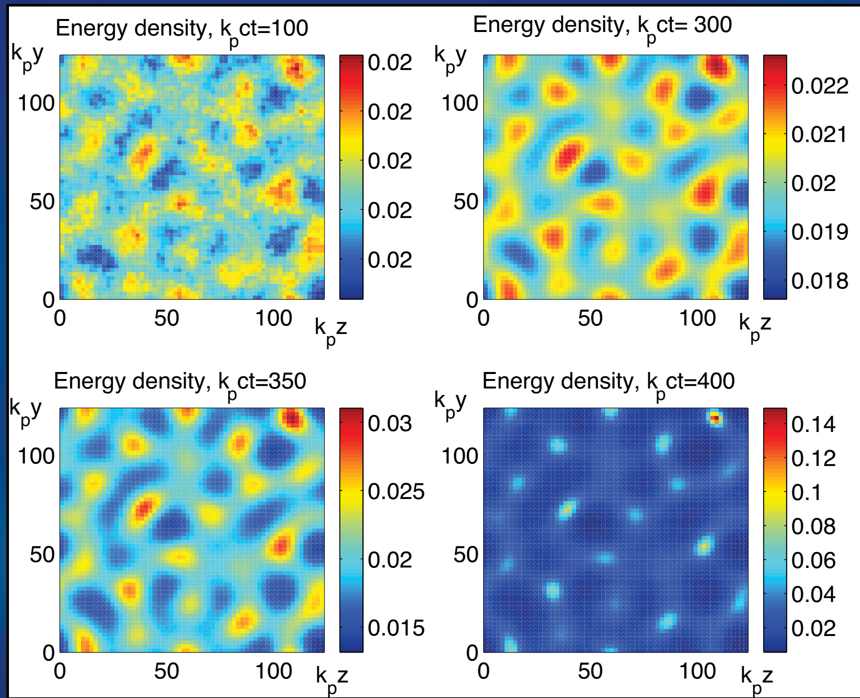
$$i\partial_t E + \tfrac{1}{2}v_g'\nabla_\perp^2 E + \mu\mathcal{E}E = 0$$

$$\left(\partial_t^2 - \tfrac{1}{3}c^2\nabla^2\right)\mathcal{E} = \nu\nabla^2|E|^2$$

(PRL **91**, 163601 (2003))

# Vacuum dynamics



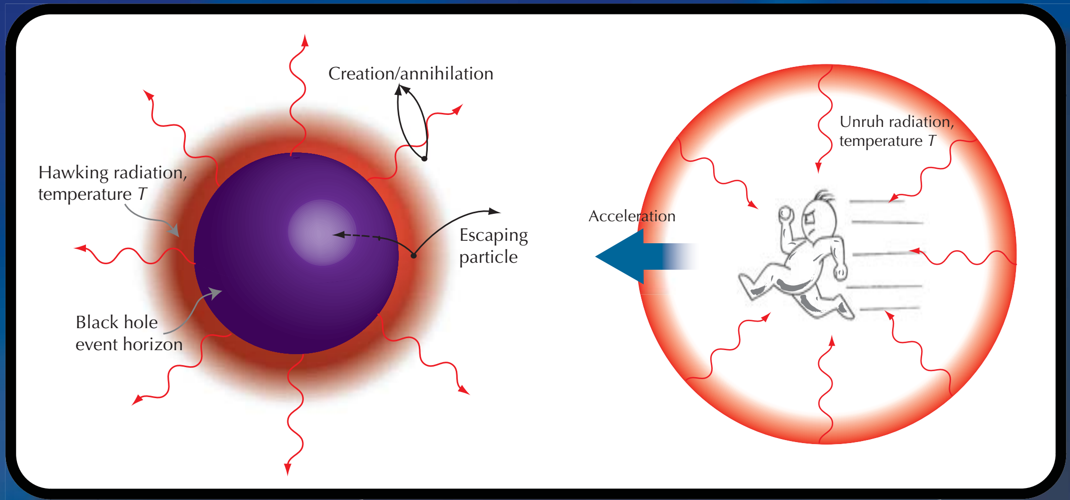



# Gigagauss laboratory fields

- Currently, gigagauss laboratory fields generated in solid-laser interactions.
- Magnetization of the vacuum for future lasers?
- Principle: magnetic field exerts Lorentz force on vacuum fluctuations.
- Possible to use for QED experiments, or to muddled?

# Hawking–Unruh effect

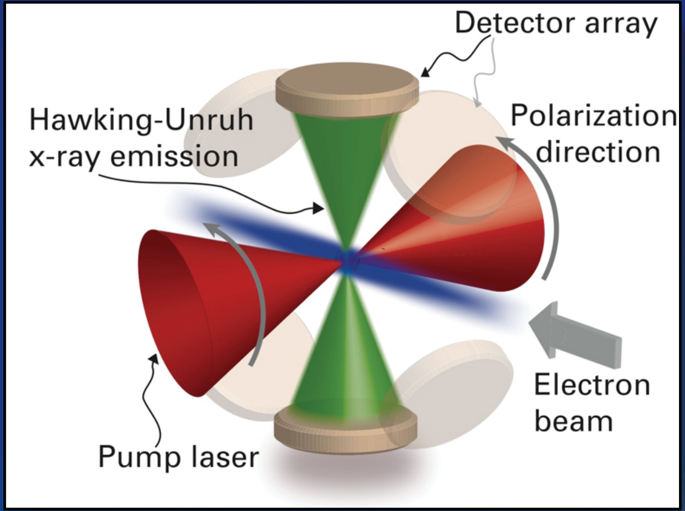
- Testing the Hawking–Unruh effect (Chen & Tajima, PRL, 1999; Schützhold *et al.*, PRL, 2006, 2008; Brodin et al., CQG, 2008); electron acceleration.

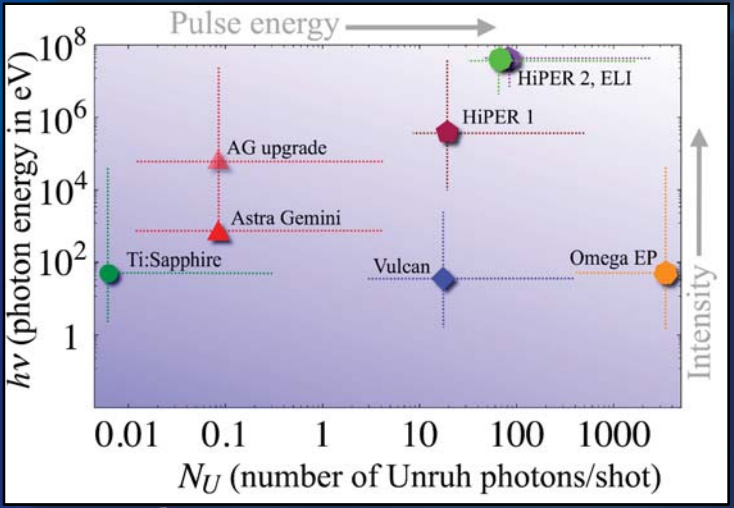



$$k_B T_H = \frac{\hbar g}{2\pi c} \qquad k_B T_U = \frac{\hbar a}{2\pi c}$$

# Unruh effect

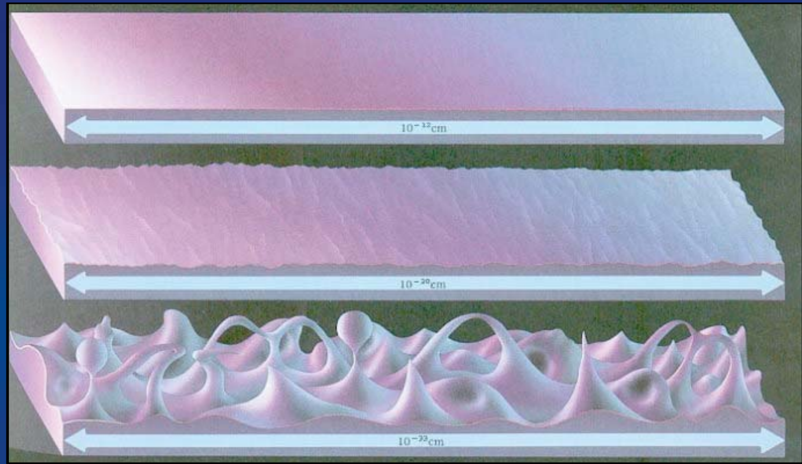
- Need electrons plasma to get measurable signal.
- Problem: hole in Larmor radiation pattern decreases like $1/N$ for $N$-electron plasma.
- Use spectral pattern; detectable soft x-ray signal from Unruh effect?
- Achievable by present day high-intensity lasers.
- Connection: dynamical Casimir?




Class. Quantum Grav., 2008

# Quantum aspects of spacetime



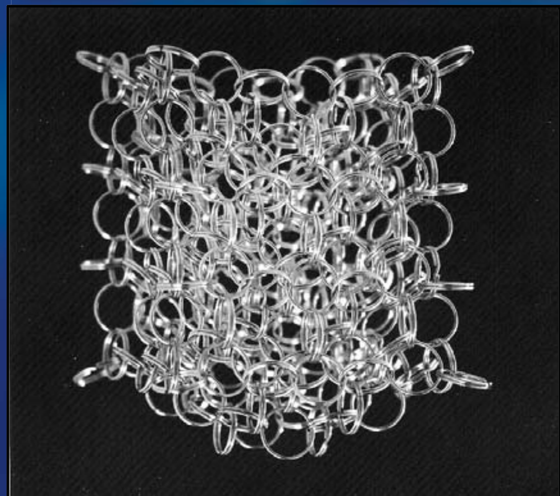
- Non-commutative spacetime

$$[x^\mu, x^\nu] = i\theta^{\mu\nu}$$

QFT on NCST interpreted as low-energy limit of open strings *or* limit on length scales. IR/UV mixing: high-energy affects low-energy.

- Canonical quantum gravity and loop quantum gravity: spacetime quantization, coarsening.

- String theory: low-energy case give birefringence-free nonlinear electrodynamics.



http://www.cpt.univ-mrs.fr/~rovelli/

# Quantum aspects of spacetime

- Effects through parametrized generalized Maxwell–Dirac system (Lämmerzahl, Appl. Phys. B, 2006)
  - Birefringence.
  - Anisotropic speed of light.
  - Anisotropy in quantum fields.
  - Violations of universality of free fall and the universality of the gravitational redshift.
  - Time and space variations of "constants".
  - Charge non-conservations.
  - Anomalous dispersion.
  - Decoherence and spacetime fluctuations.
  - Modified interference.
  - Non-localities.

# Quantum aspects of spacetime

- Dispersion: invariant scale length (such as Planck scale) introduces Lorentz invariance violations (massive and massless).
- Small scale ST structure (Wheeler, Ann. Phys., 1957).
- Deformed dispersion relation (Amelino-Camelia et al., Nature, 1998)

$$c^2k^2 = \omega^2\left(1 \pm \xi\frac{\hbar\omega}{E_{QG}}\right), \qquad E_{QG} \overset{?}{\sim} 10^{19}\,\mathrm{GeV}$$

  From NCST and LQG. Test through $\gamma$-ray bursts.

- Possibility for *coherent* states: “nonlocality” and bulk property (Magueijo, PRD, 2006; Hossenfelder, PRD, 2007)

$$\xi = \xi(|A|) \sim \xi_0|A|^a$$

# Conclusions

- Laser science is entering a new era:
  - Relativistic optics.
  - Nonlinear quantum vacuum.
- Possible to experimentally probe uncharted QED sectors.
- Atomic systems in ultra-intense fields.
- Laser probes of elastic photon-photon scattering.
- "Clean" experiment, benchmark experiment?
- Interesting future possibilities:
  - Collective quantum vacuum effects.
  - Higher harmonic generation.
  - Unruh test, dynamical Casimir effect, accelerated mirrors?.